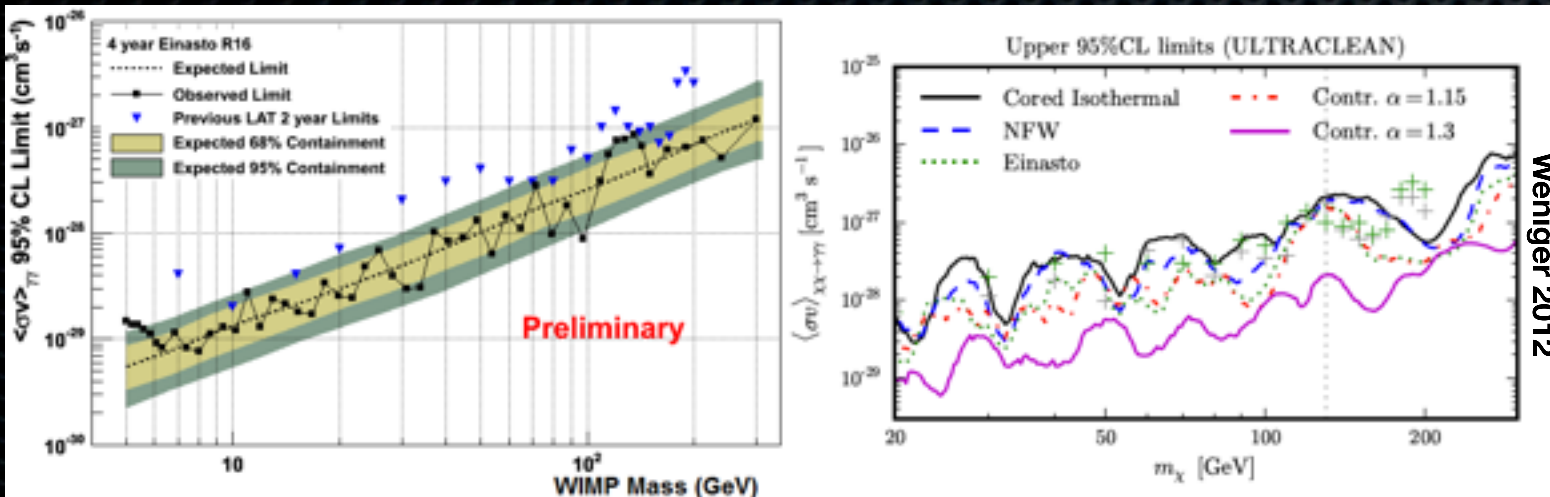
# Complementarity of Indirect Searches via Gamma-rays

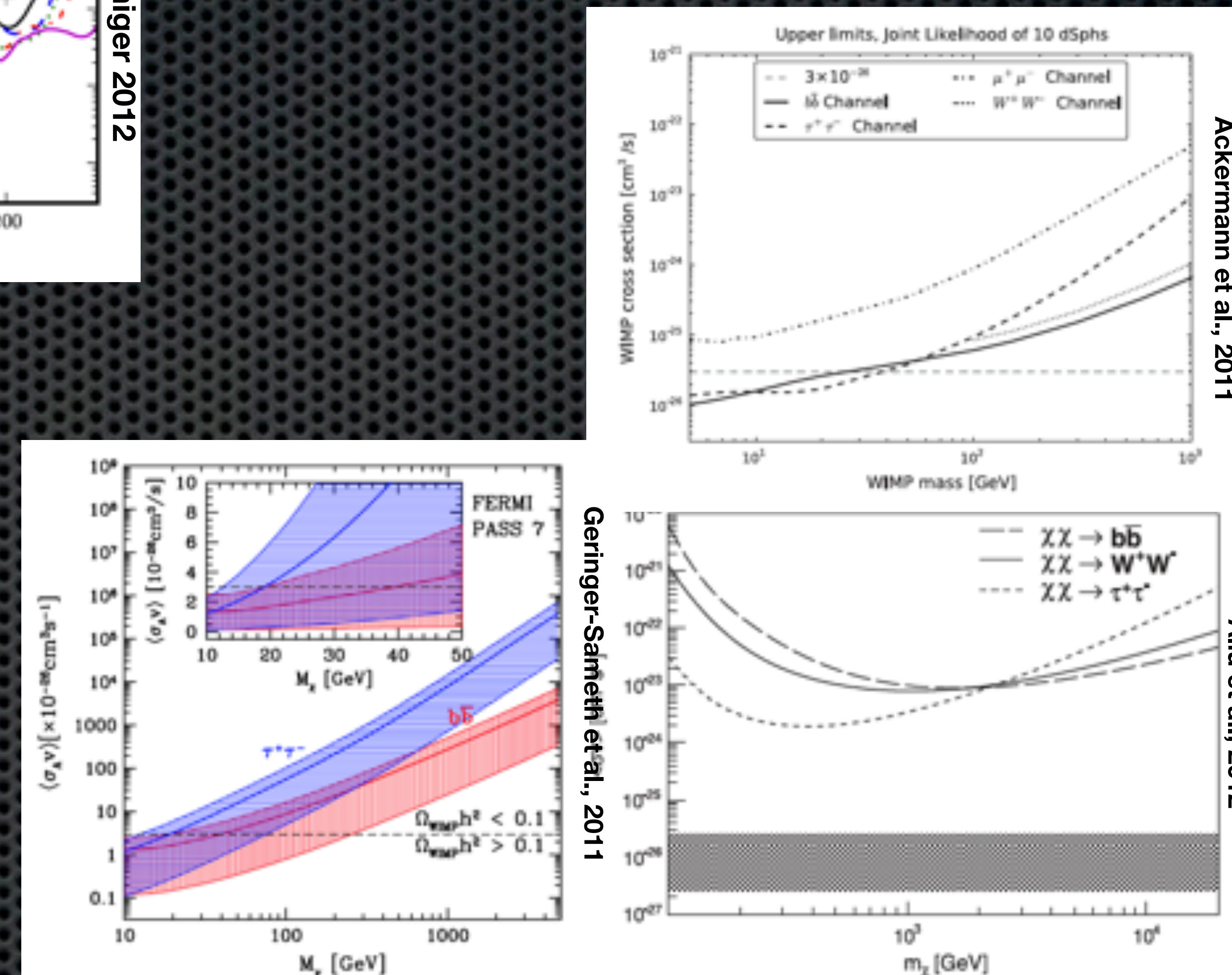

**Alex Drlica-Wagner**

**with Matthew Cahill-Rowley, Randy Cotta, Stefan Funk, JoAnne Hewett, Ahmed Ismail, Tom Rizzo, and Matthew Wood**

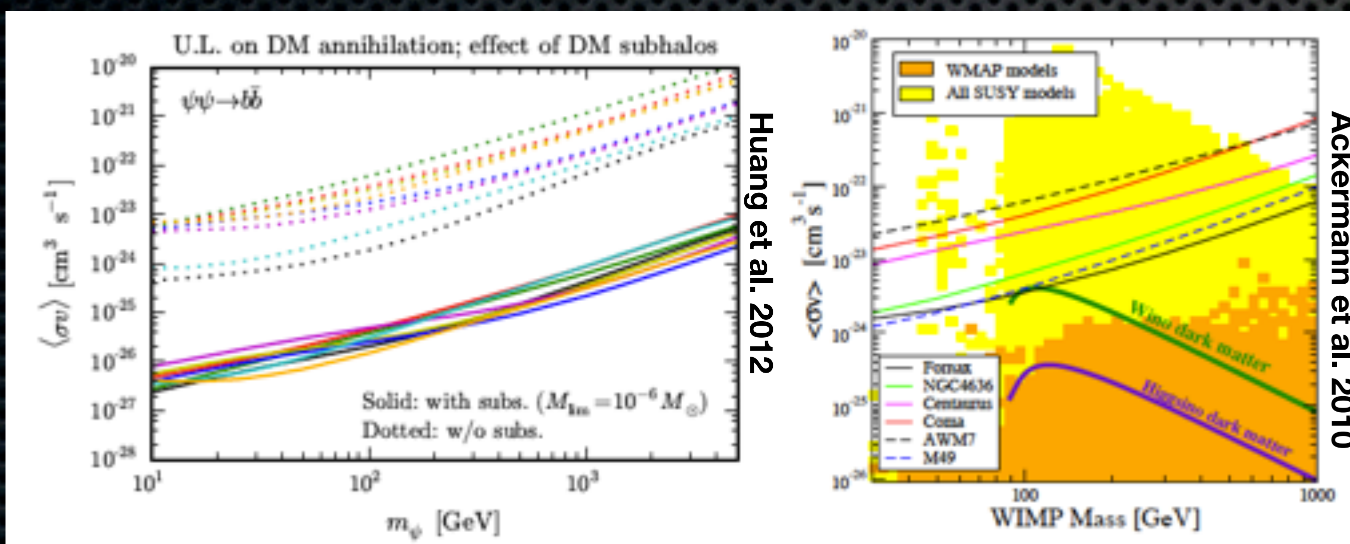
# Spectral Lines



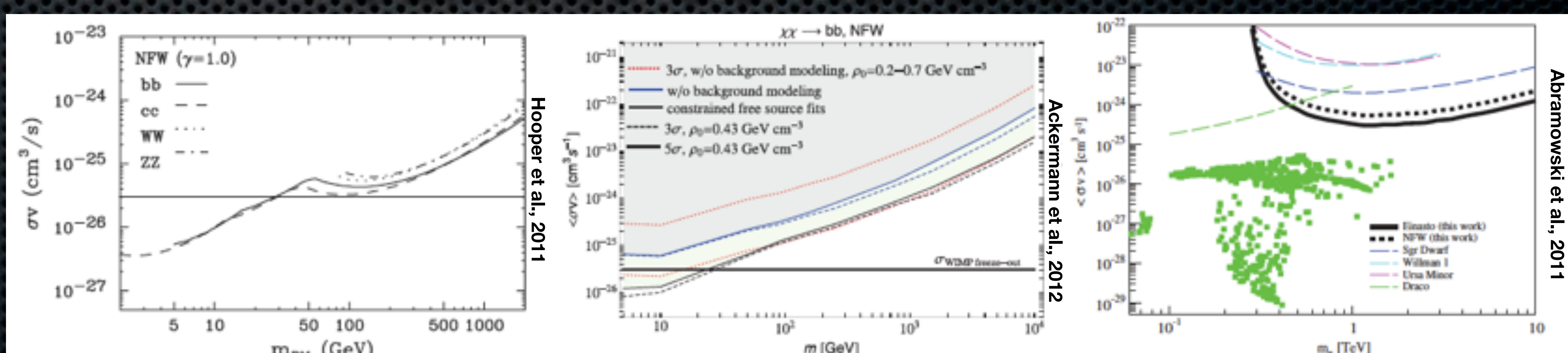

# Dwarf Galaxies

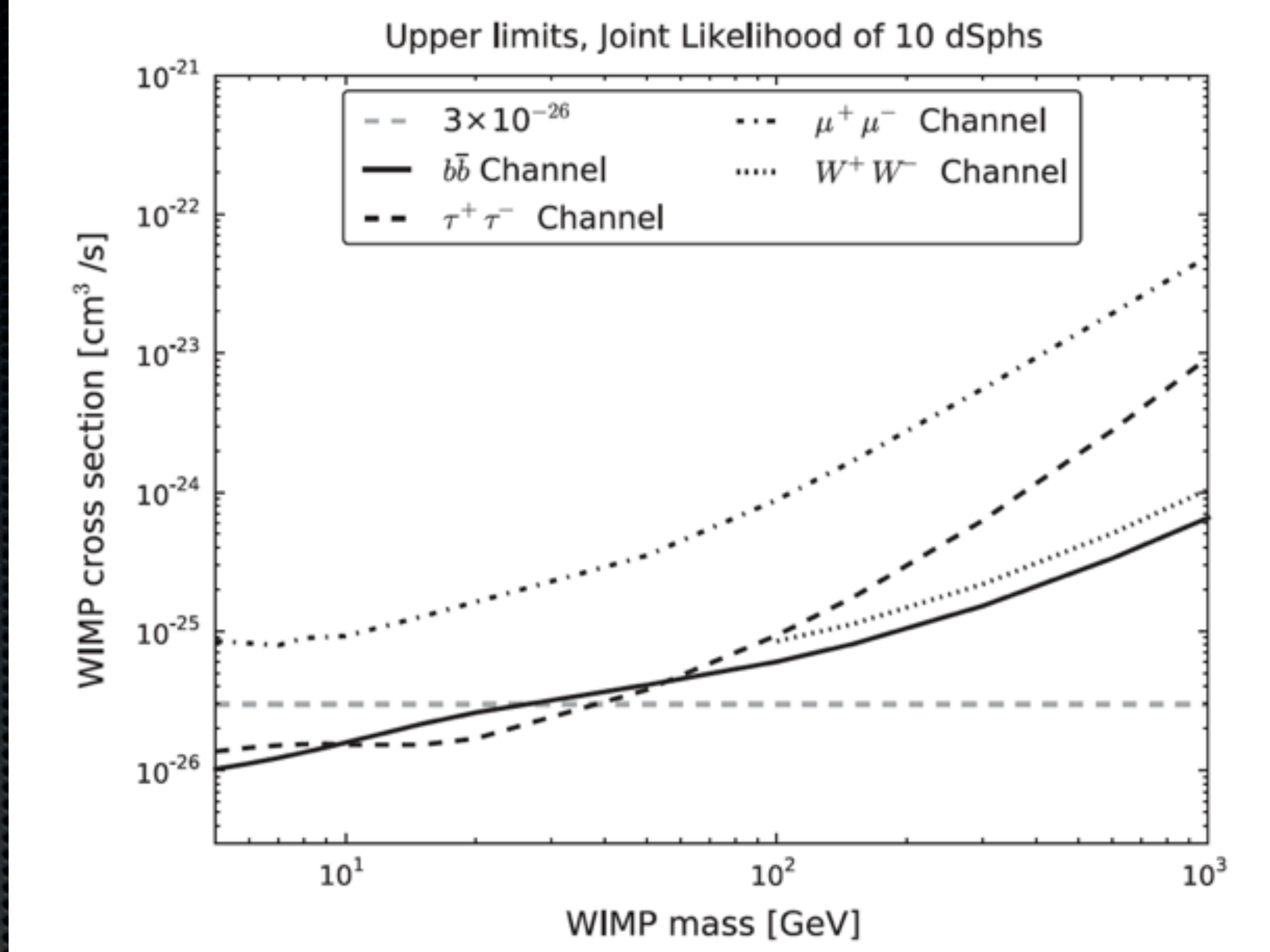



# Galaxy Clusters

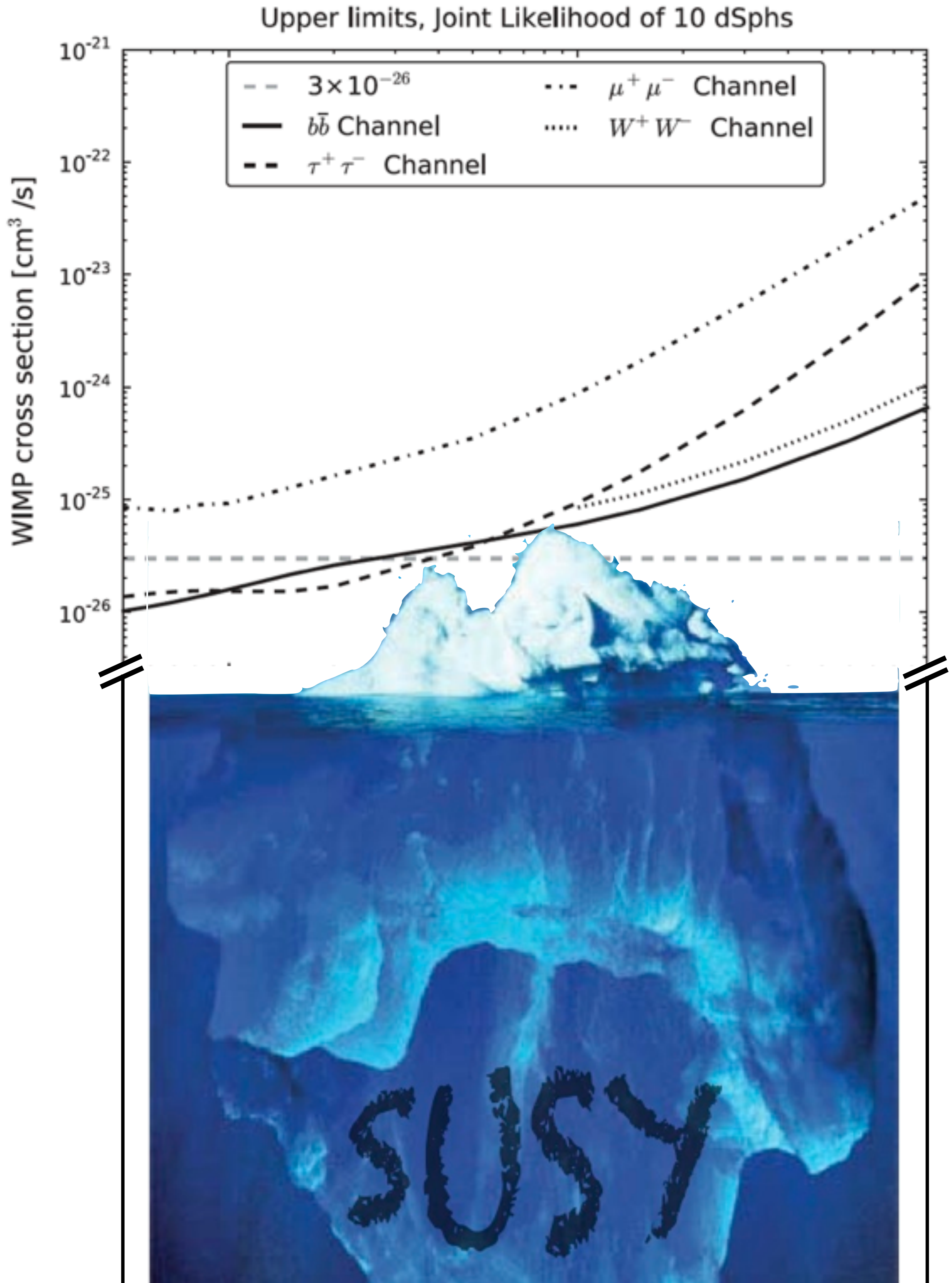



# Galactic Center and Halo





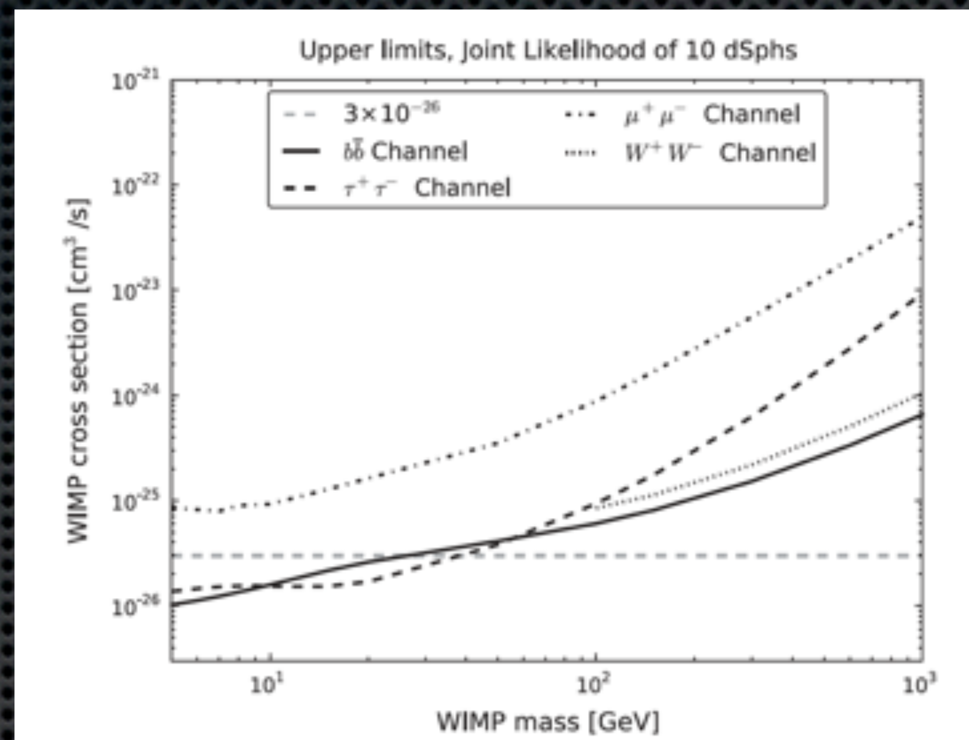
Upper limits, Joint Likelihood of 10 dSphs
$3\times10^{-26}$
$b\bar{b}$ Channel
$\tau^+\tau^-$ Channel
$\mu^+\mu^-$ Channel
$W^+W^-$ Channel
WIMP cross section [cm$^3$ /s]
WIMP mass [GeV]
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
$10^{-26}$
$10^1$
$10^2$
$10^3$



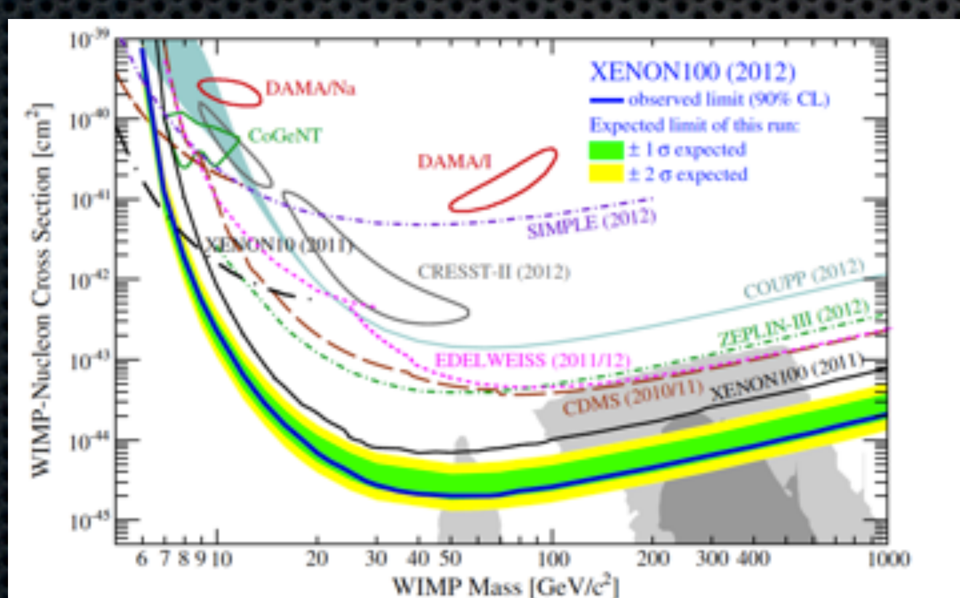
Upper limits, Joint Likelihood of 10 dSphs
$3\times10^{-26}$
$b\bar{b}$ Channel
$\tau^+\tau^-$ Channel
$\mu^+\mu^-$ Channel
$W^+W^-$ Channel
WIMP cross section [$cm^3$ /s]
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
$10^{-26}$
SUSY

# Complementarity

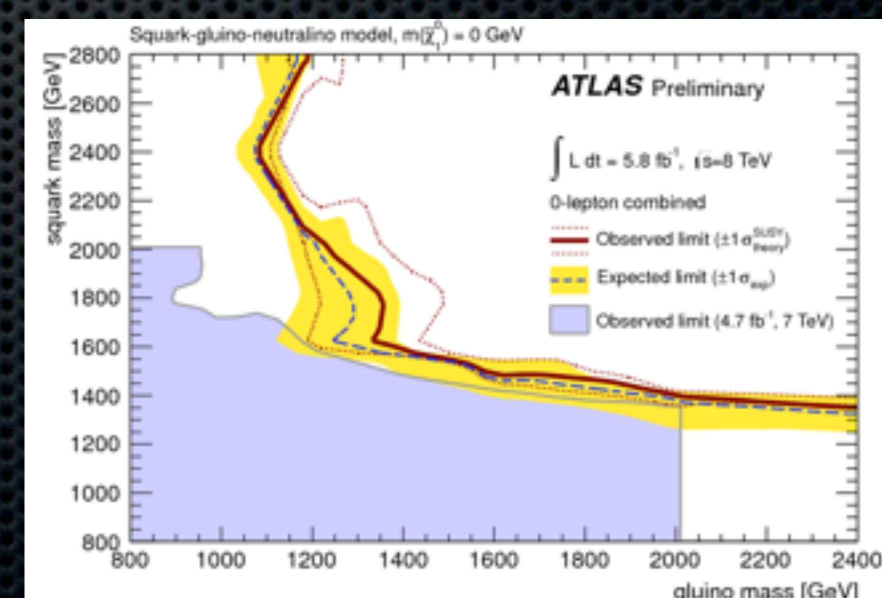
## Indirect Detection



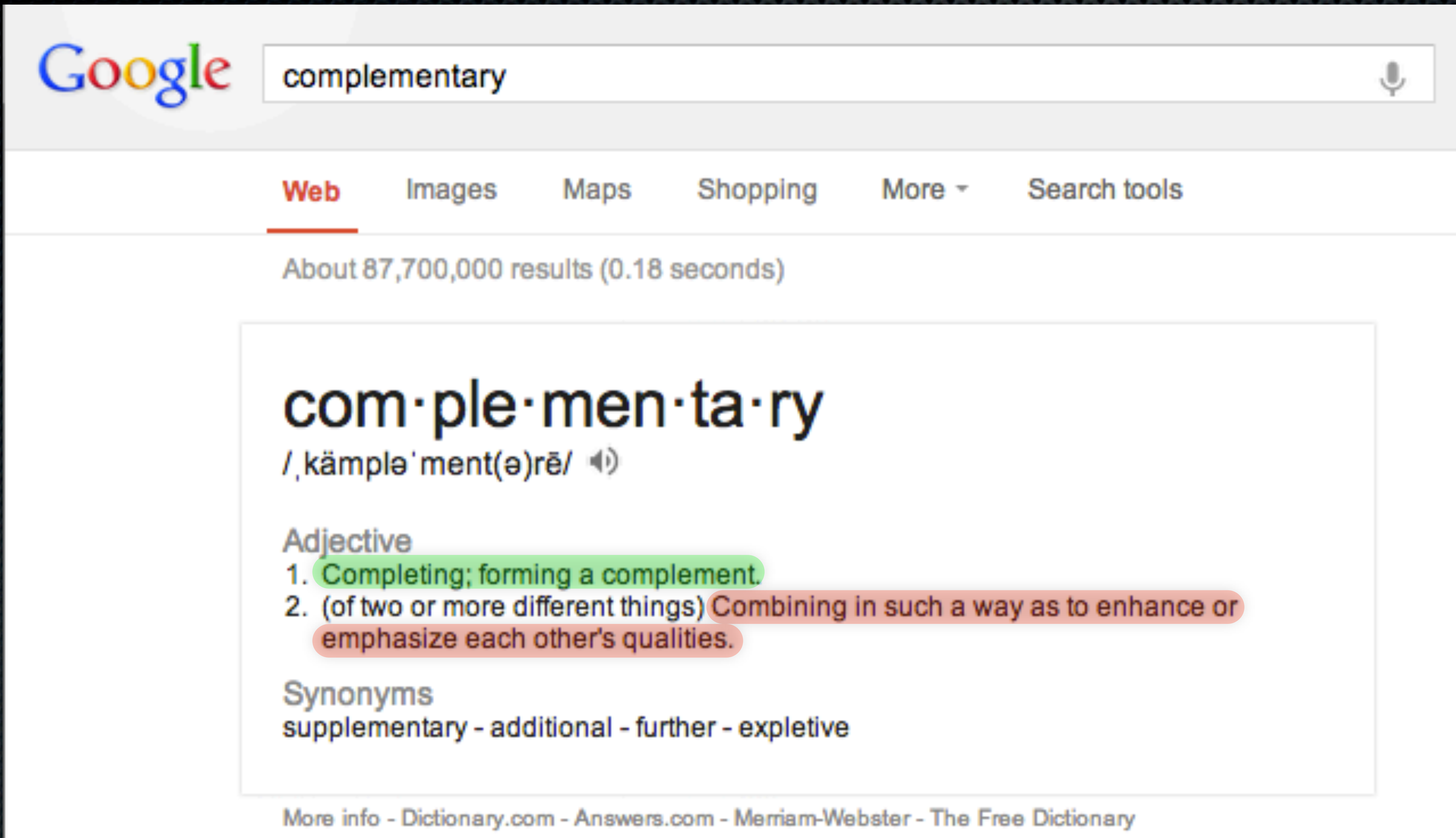

## Direct Detection



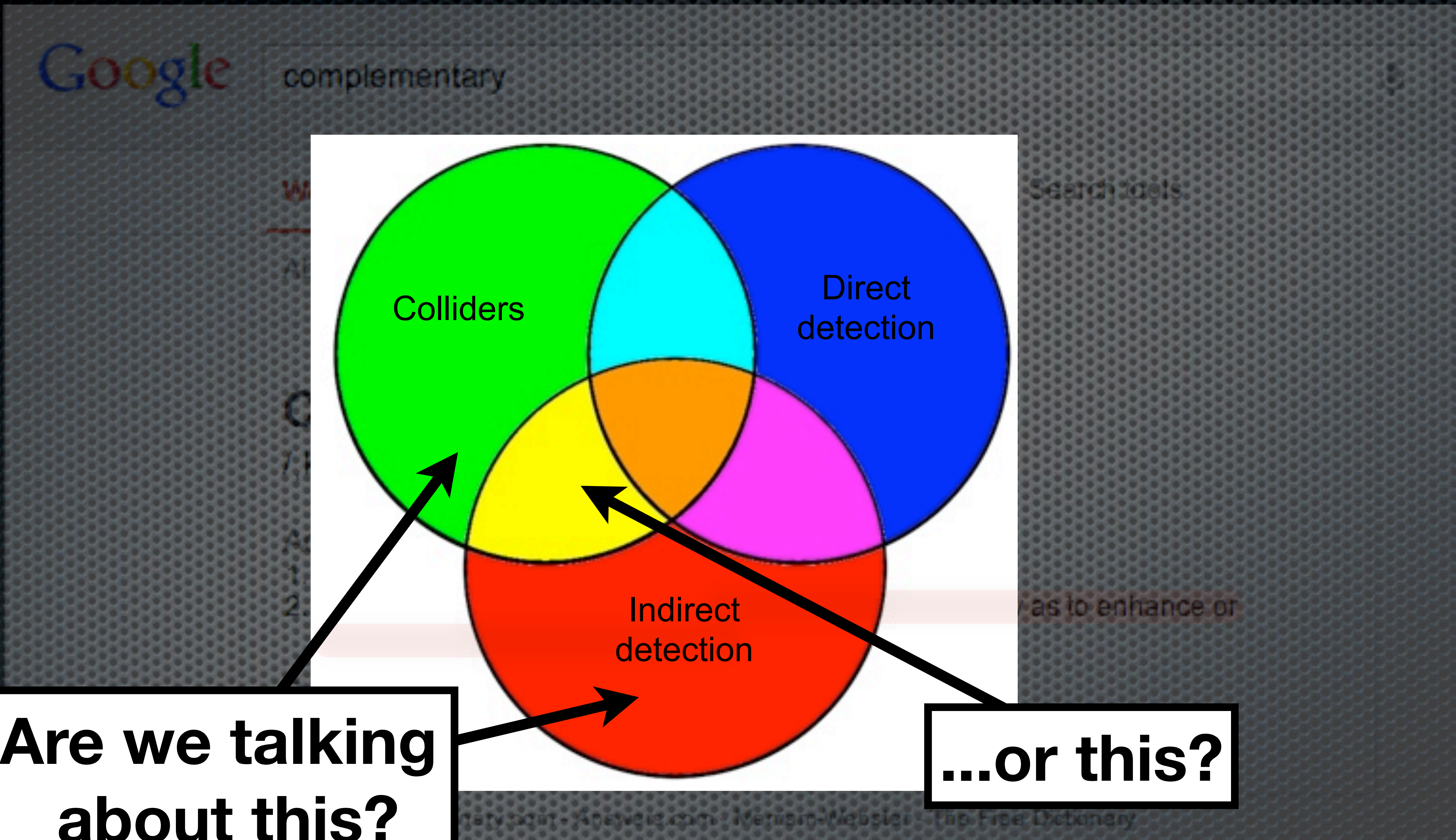

## Colliders



# Complementarity



# Complementarity




**Are we talking about this?**

**...or this?**

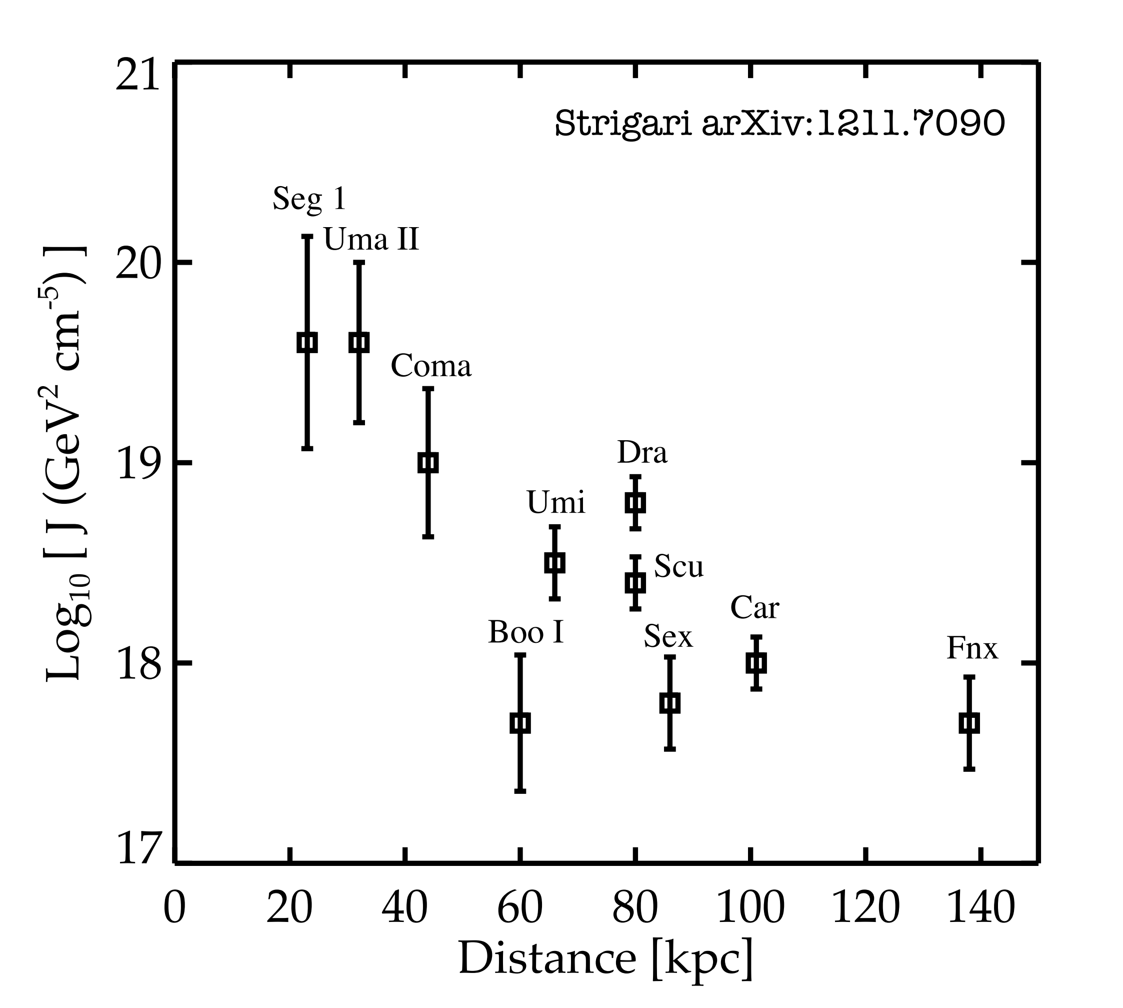
# Phenomenological MSSM

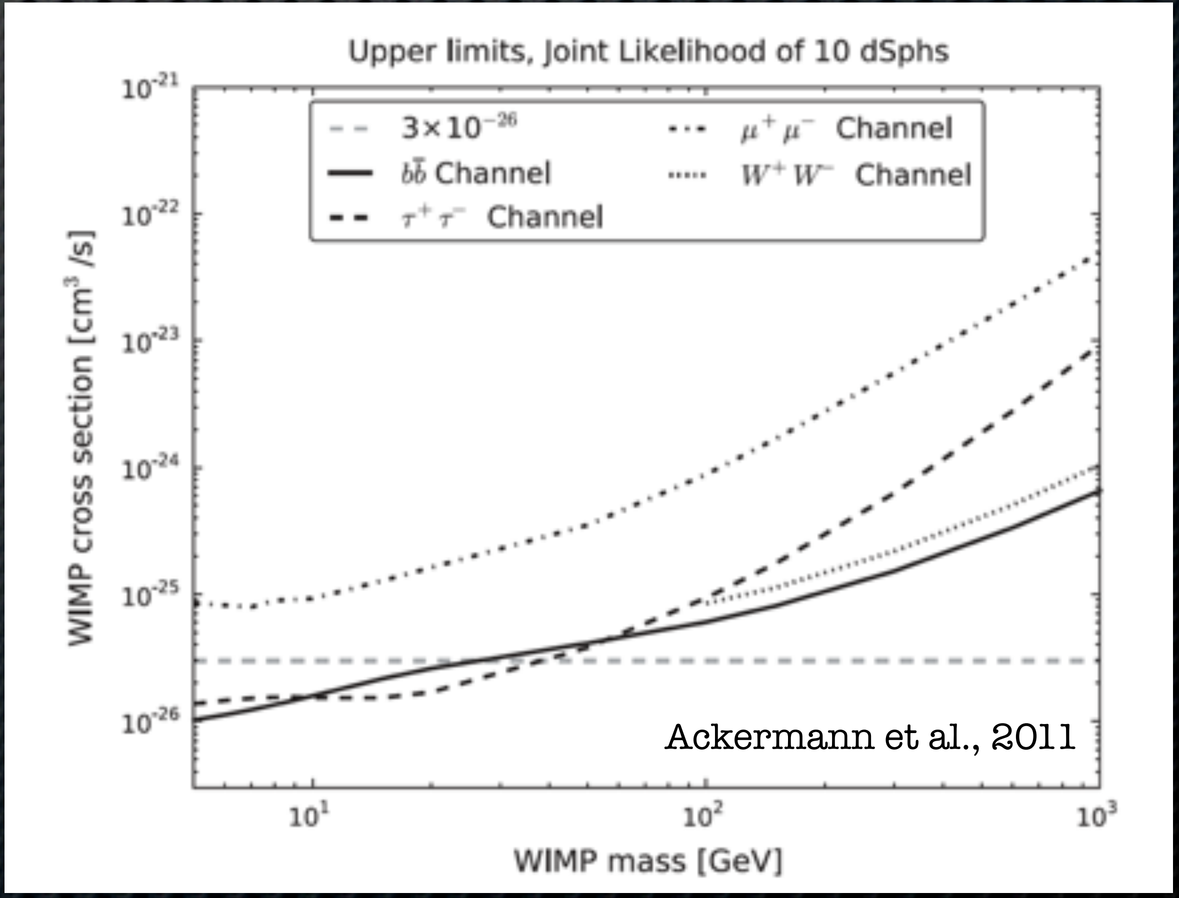
- Study detectability of SUSY DM in the context of the Phenomenological MSSM (pMSSM; Berger et al. 2009)
    - More flexibility that highly constrained MSSM scans (i.e. cMSSM or mSUGRA)
    - Describe the range allowed physics rather than the “best-fit” SUSY models
- Model set generated from a numerical scans over the 19-dimensional parameter space of the pMSSM parameters (see Cotta et al. 2011, Cahill-Rowley et al. 2012)
    - 10 squark masses, 3 gaugino masses, 3 tri-linear couplings, 3 Higgs sector parameters
- Apply current experimental constraints:
    - Collider searches; CMS/ATLAS
    - Direct Detection WIMP-Nucleon Cross Section Limits (XENON100)
    - Upper bound on WIMP Relic Density (WMAP7): $\Omega_{DM}\, h^2 < 0.123$
- ~200k model points survive, each of which have uniquely described observables

**More details in talks by A. Ismail (Thurs.), R. Cotta (Thurs.), M. Wood (Thurs.), M. Cahill-Rowley (Thurs.), T. Rizzo (Fri.), R. Cotta (Fri.)**

# Fermi-LAT Observations of Dwarf Galaxies

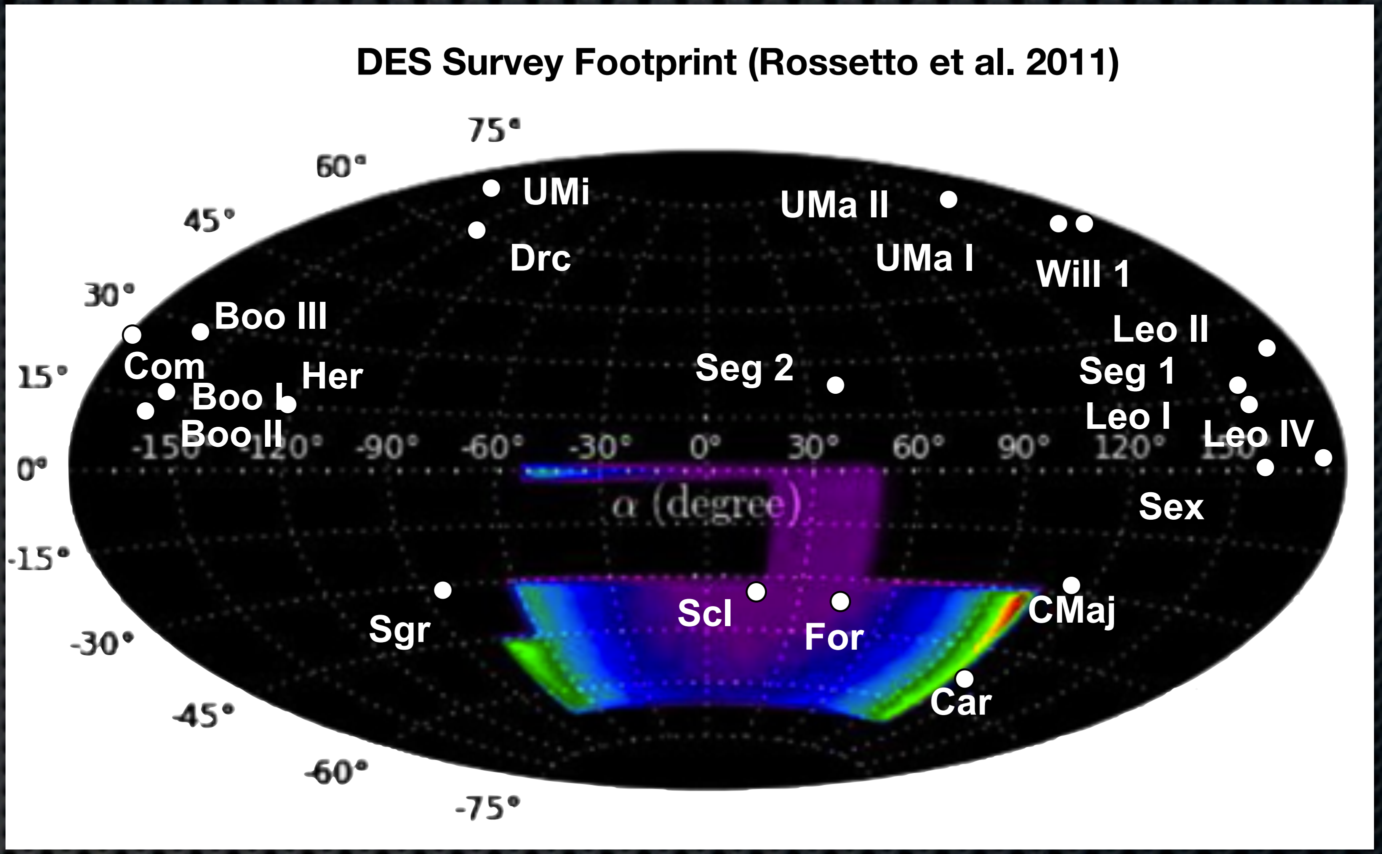
- Dwarf galaxies are some of the most dark matter dominated objects in the universe
- Dark matter content can be assessed through the study of stellar kinematics
- Assume that the same dark matter particle in all dwarf spheroidal galaxies
- Perform a combined likelihood analysis of multiple dwarfs with 2 years of data
    - Predicted flux for each dwarf will depend on individual dark matter content (J-factor)
    - Statistical uncertainties in J-factor determined from stellar kinematic data.
    - Fit backgrounds independently for each dwarf
- Include uncertainty in the dark matter content as nuisance parameters in the likelihood

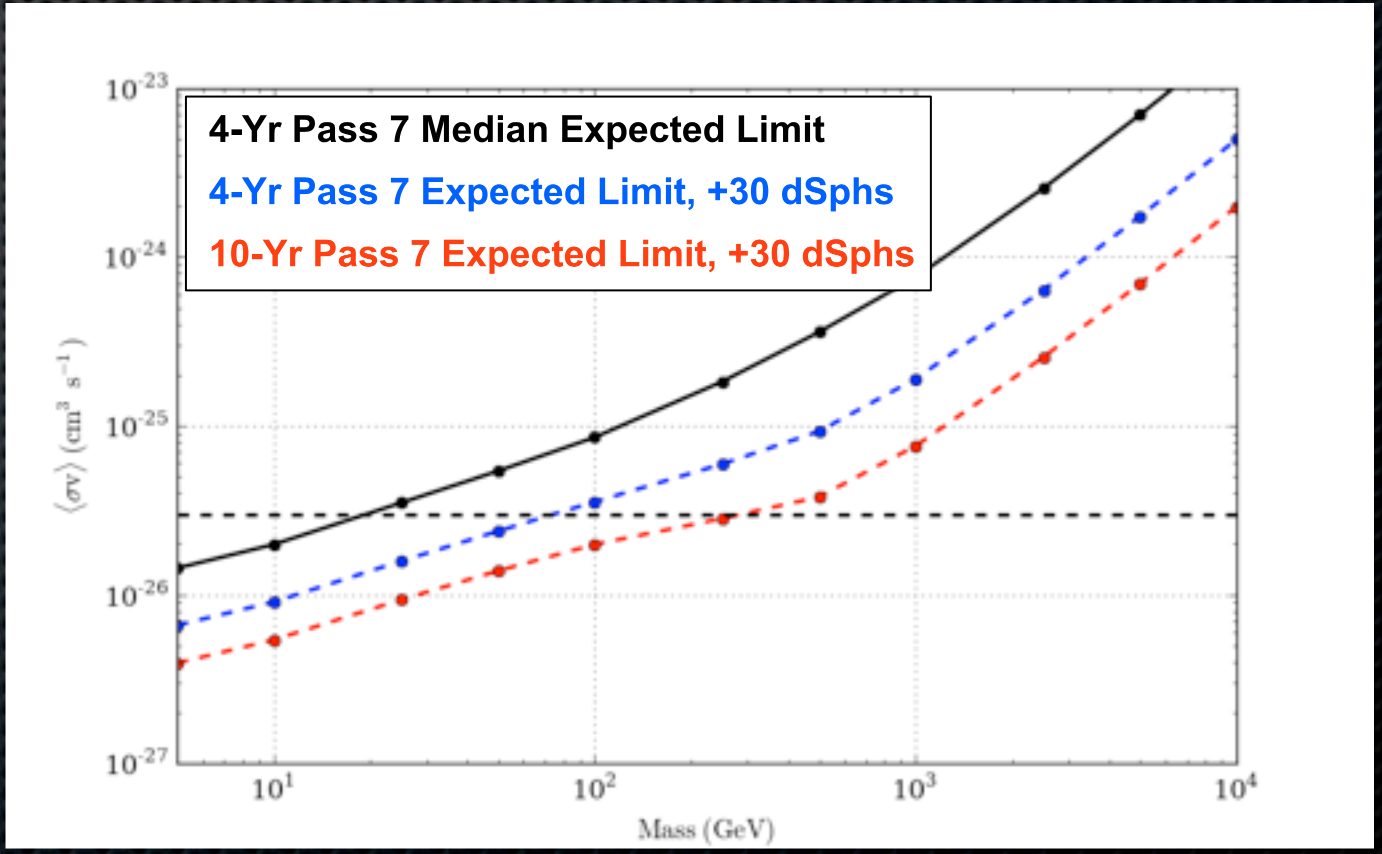


# Future Observations

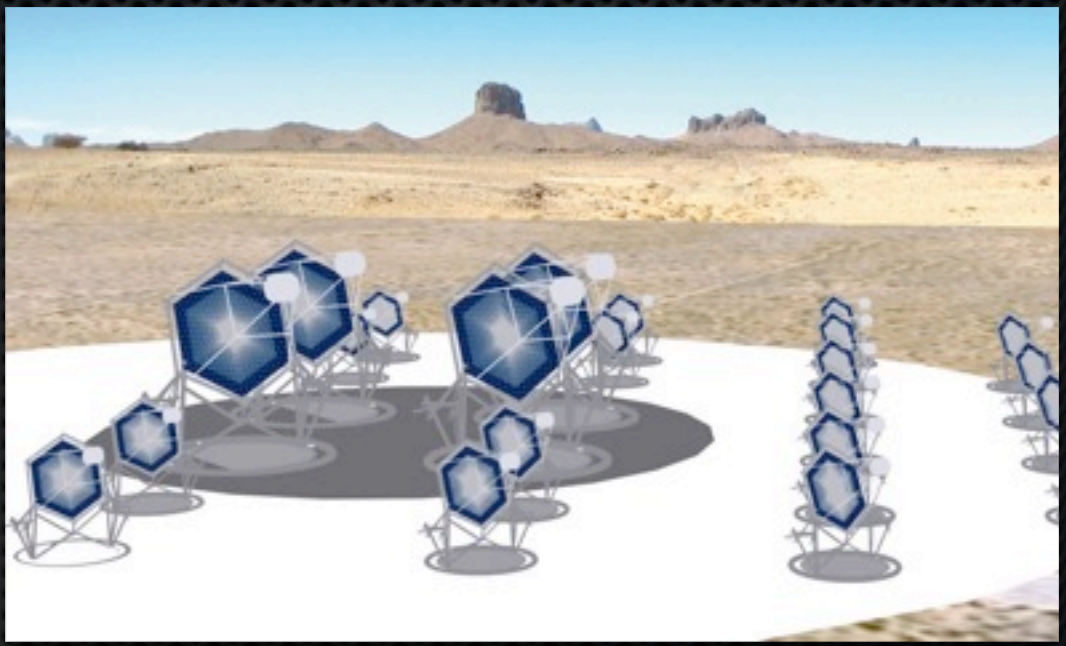
- Improvements to the LAT dataset:
  - Longer integration time
  - Improved LAT performance
- More complete sample of dwarf galaxies:
  - DES will probe the population of faint satellite galaxy out to a radius ~120 kpc (Rossetto et al. 2011)
  - Predicted that DES could discover 19 to 37 new satellite galaxies (Tollerud et al. 2008)
- Investigate a factor of 10 increase in LAT sensitivity to dwarf galaxies.

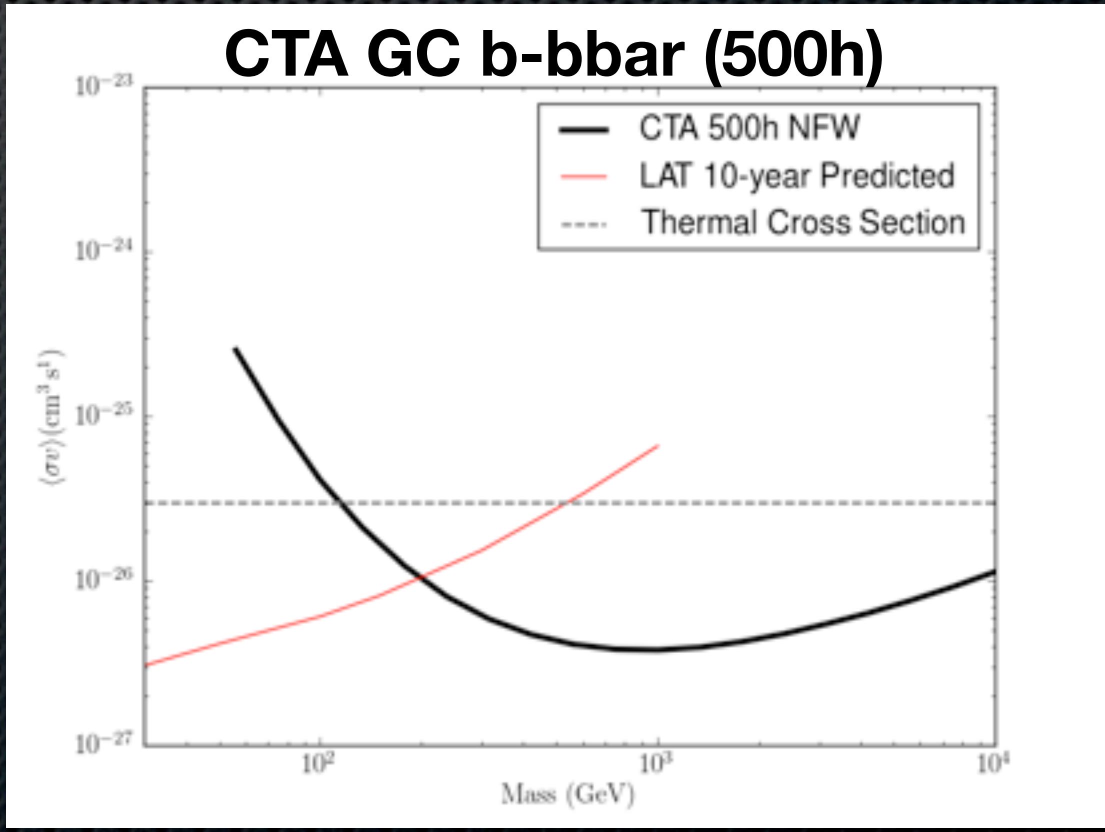


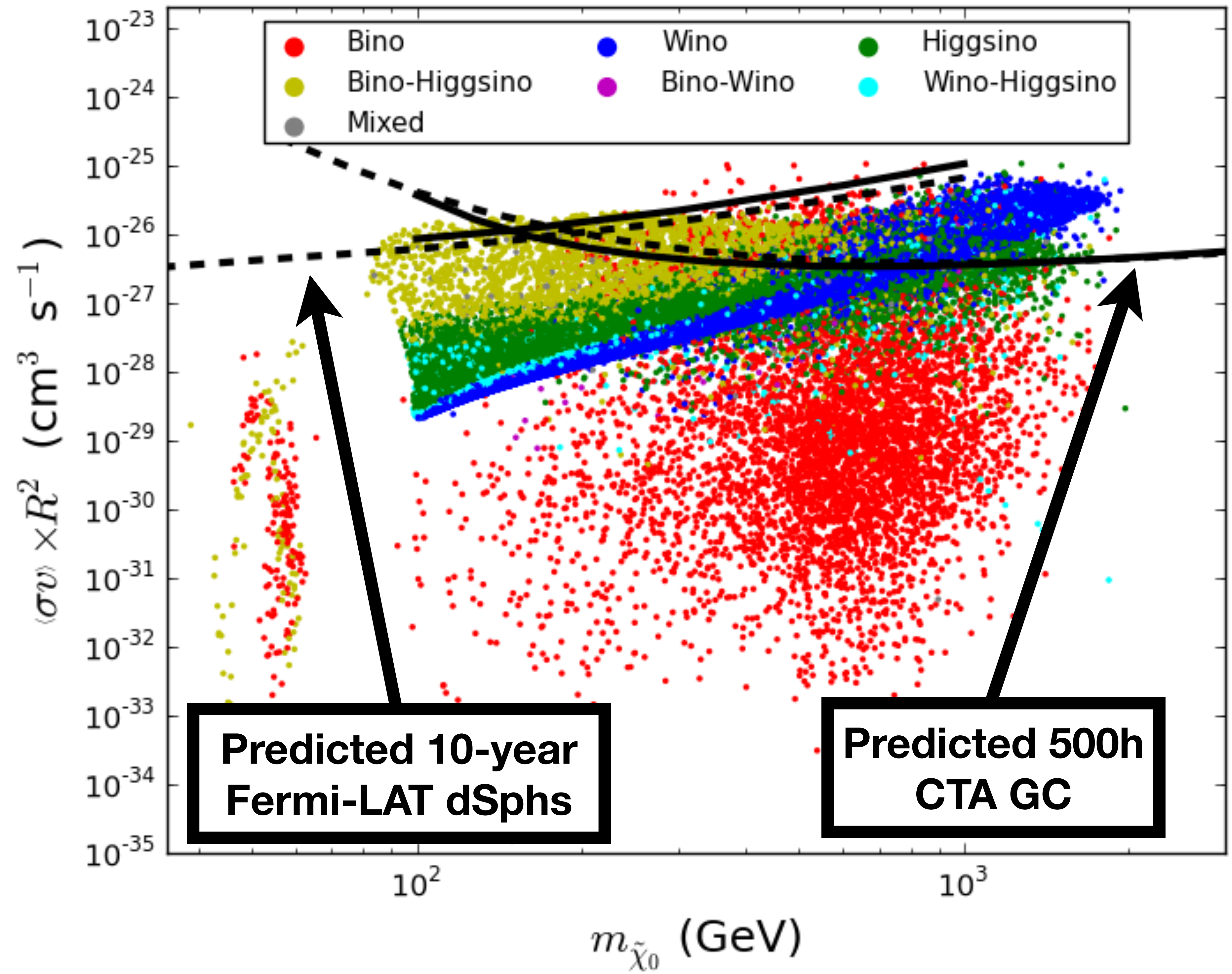
# Cherenkov Telescope Array

- Examine CTA performance including a US contribution of 36 mid-sized telescopes
- Relative to current ground-based instruments:
  - 10x increase in sensitivity
  - 10x increase in core energy range
  - Decreased energy threshold
  - Increased angular resolution
- Galactic center presents best dark matter target
  - 500h observation
  - 95% C.L. sensitivity assuming NFW profile
  - Annular region surrounding GC to minimize foregrounds (H.E.S.S.-style analysis)



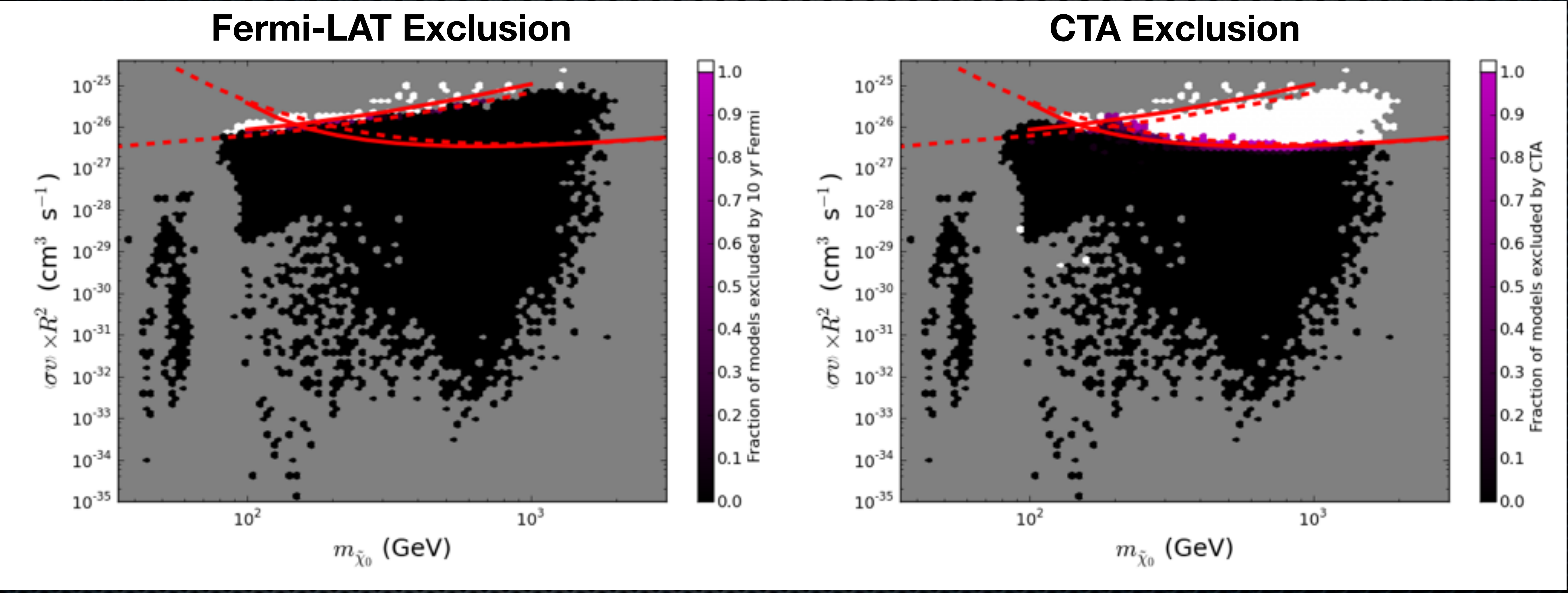


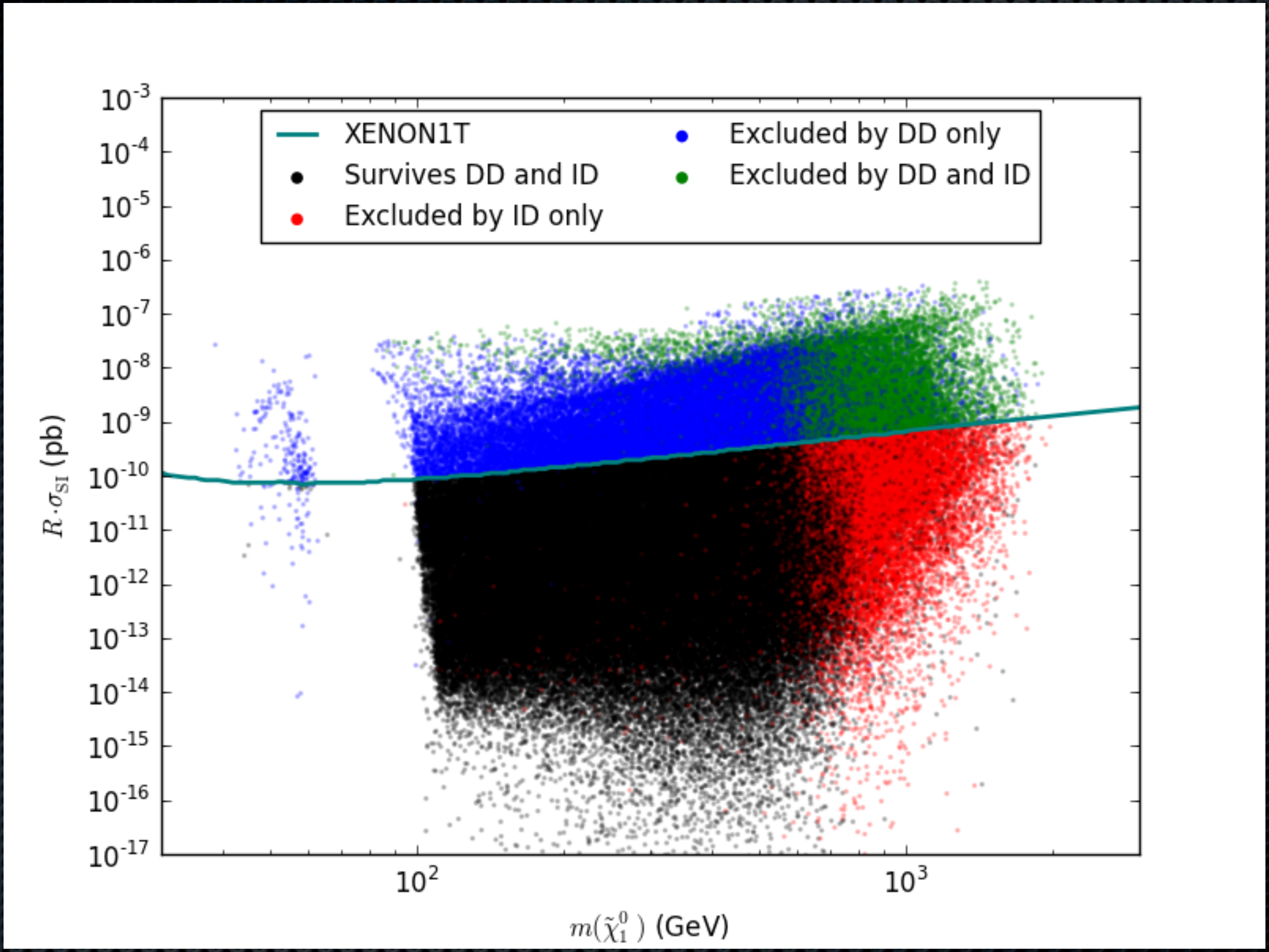

More from M. Wood (Thurs.)



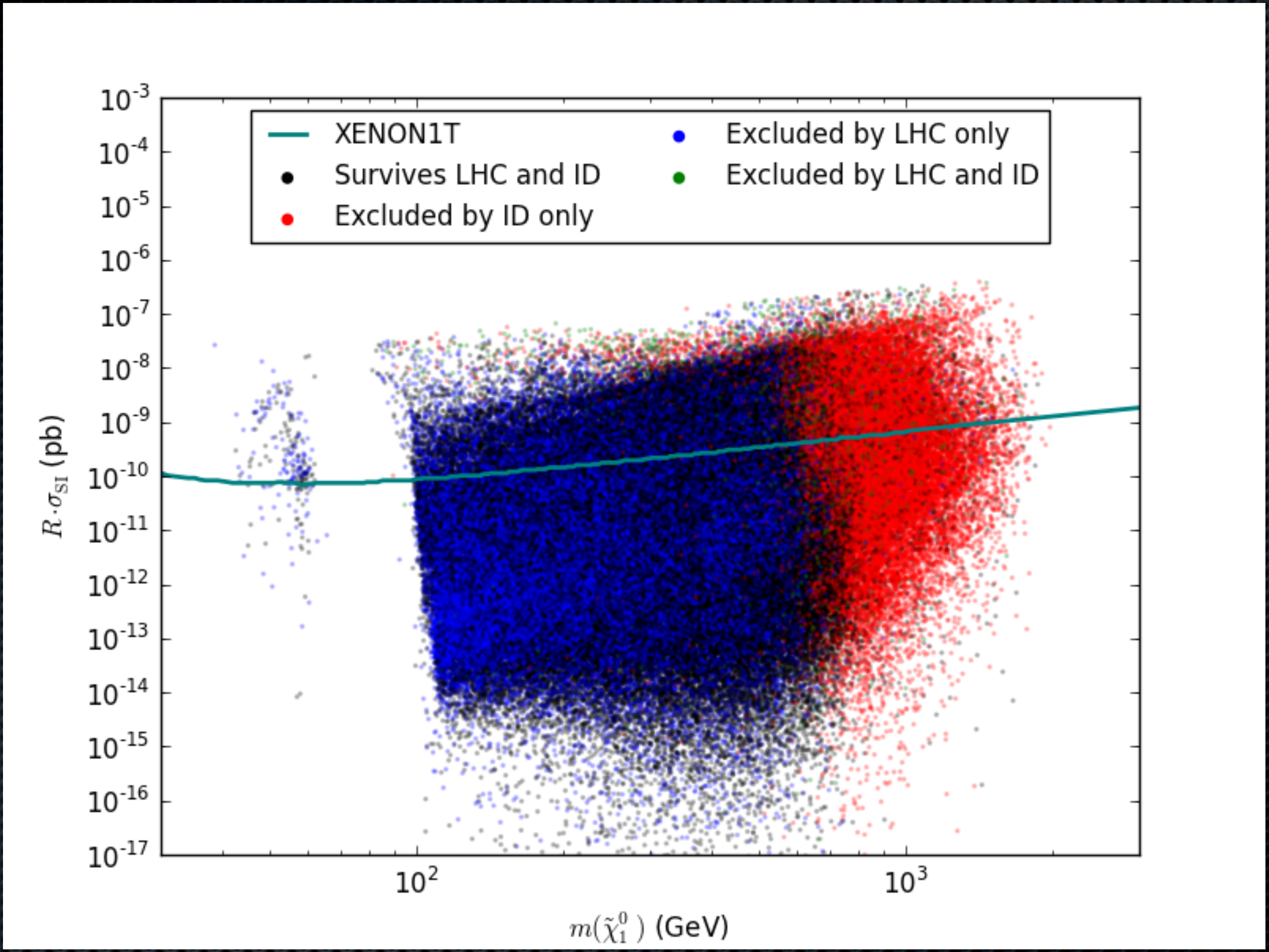
Bino
Wino
Higgsino
Bino-Higgsino
Bino-Wino
Wino-Higgsino
Mixed
$\langle\sigma v\rangle \times R^2$ (cm$^3$ s$^{-1}$)
$m_{\tilde{\chi}_0}$ (GeV)
$10^{-23}$
$10^{-24}$
$10^{-25}$
$10^{-26}$
$10^{-27}$
$10^{-28}$
$10^{-29}$
$10^{-30}$
$10^{-31}$
$10^{-32}$
$10^{-33}$
$10^{-34}$
$10^{-35}$
$10^2$
$10^3$
Predicted 10-year Fermi-LAT dSphs
Predicted 500h CTA GC

# pMSSM Exclusion Fraction

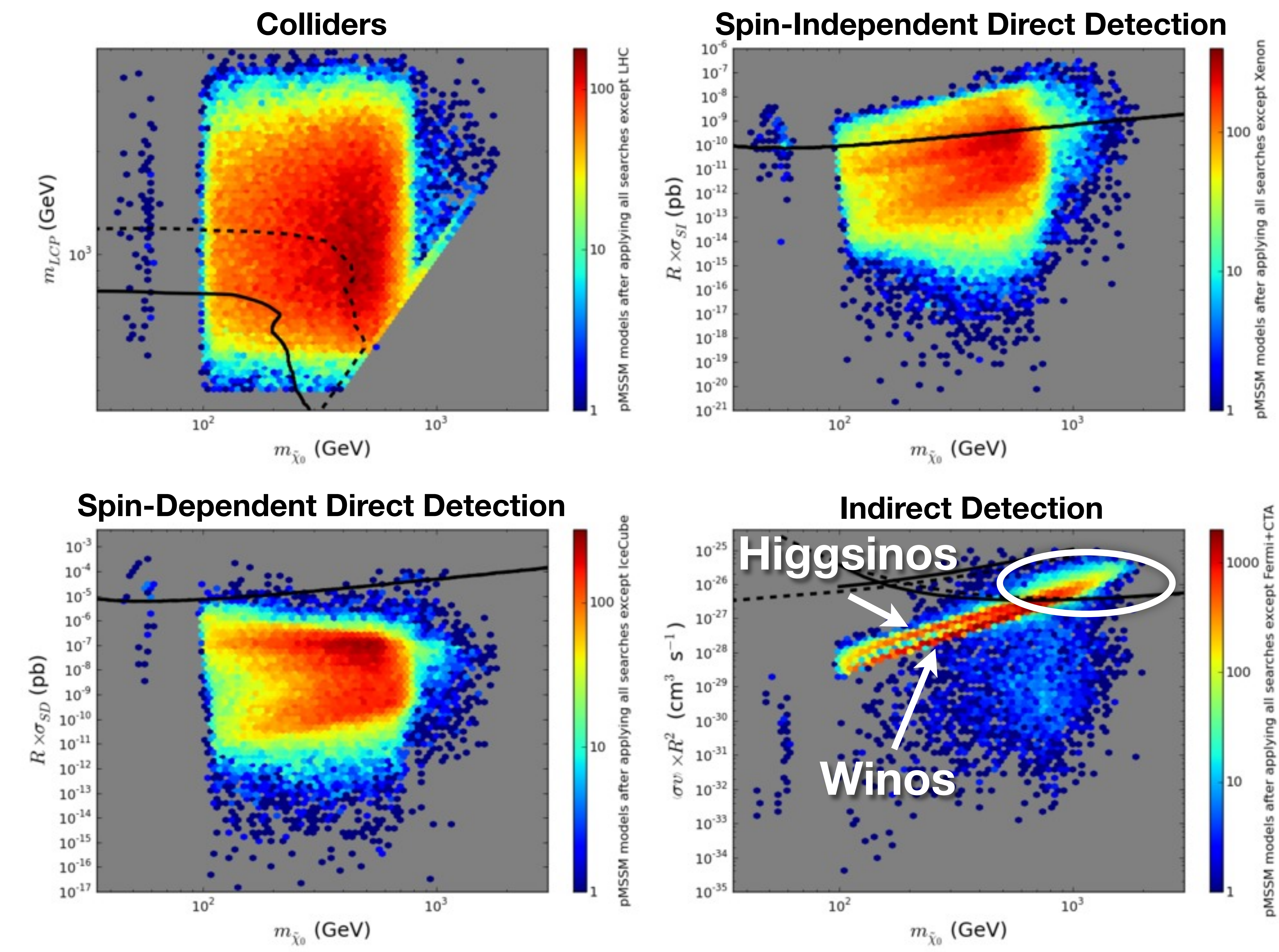




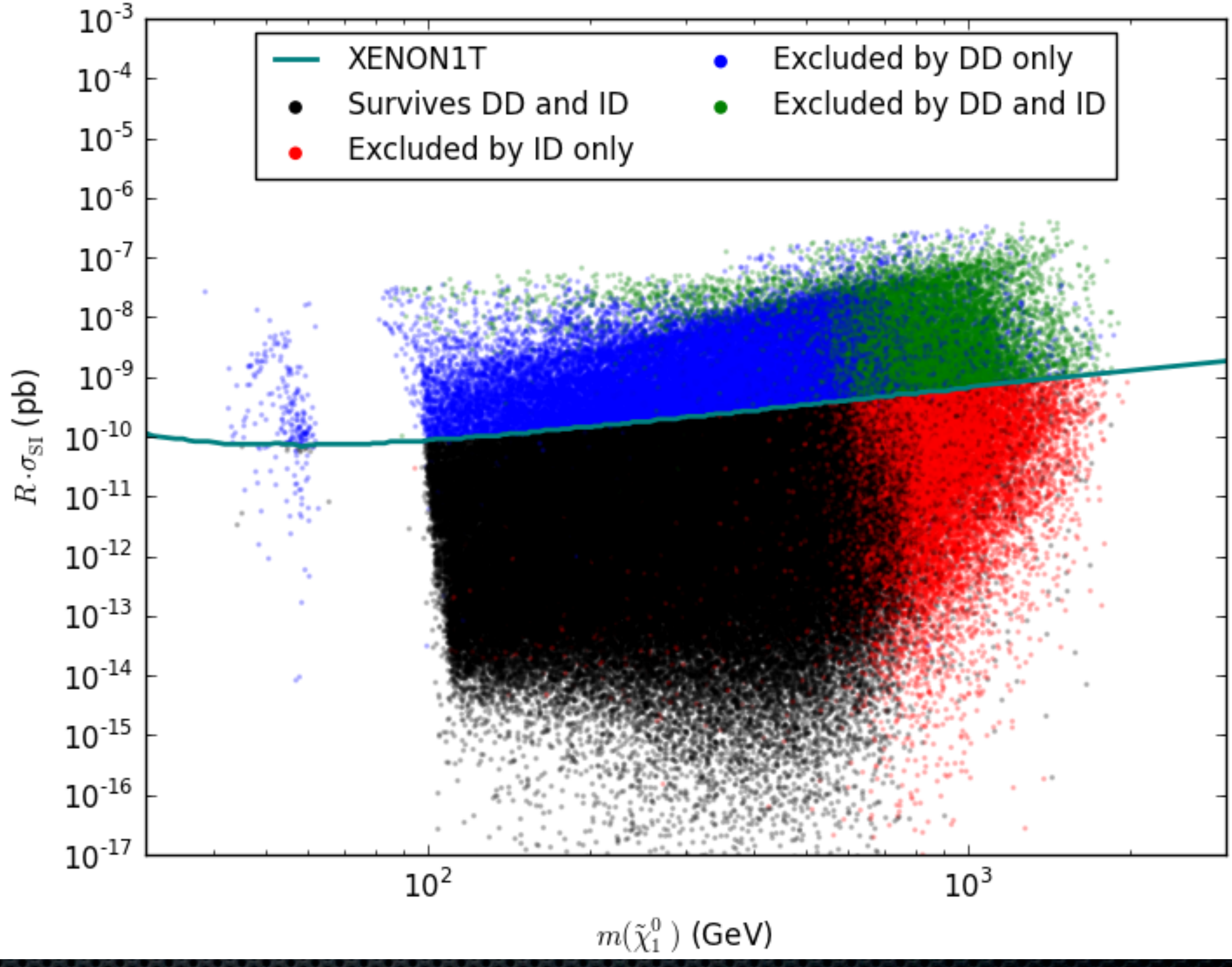
XENON1T
Survives DD and ID
Excluded by ID only
Excluded by DD only
Excluded by DD and ID
$R \cdot \sigma_{SI}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)
$10^{2}$
$10^{3}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$

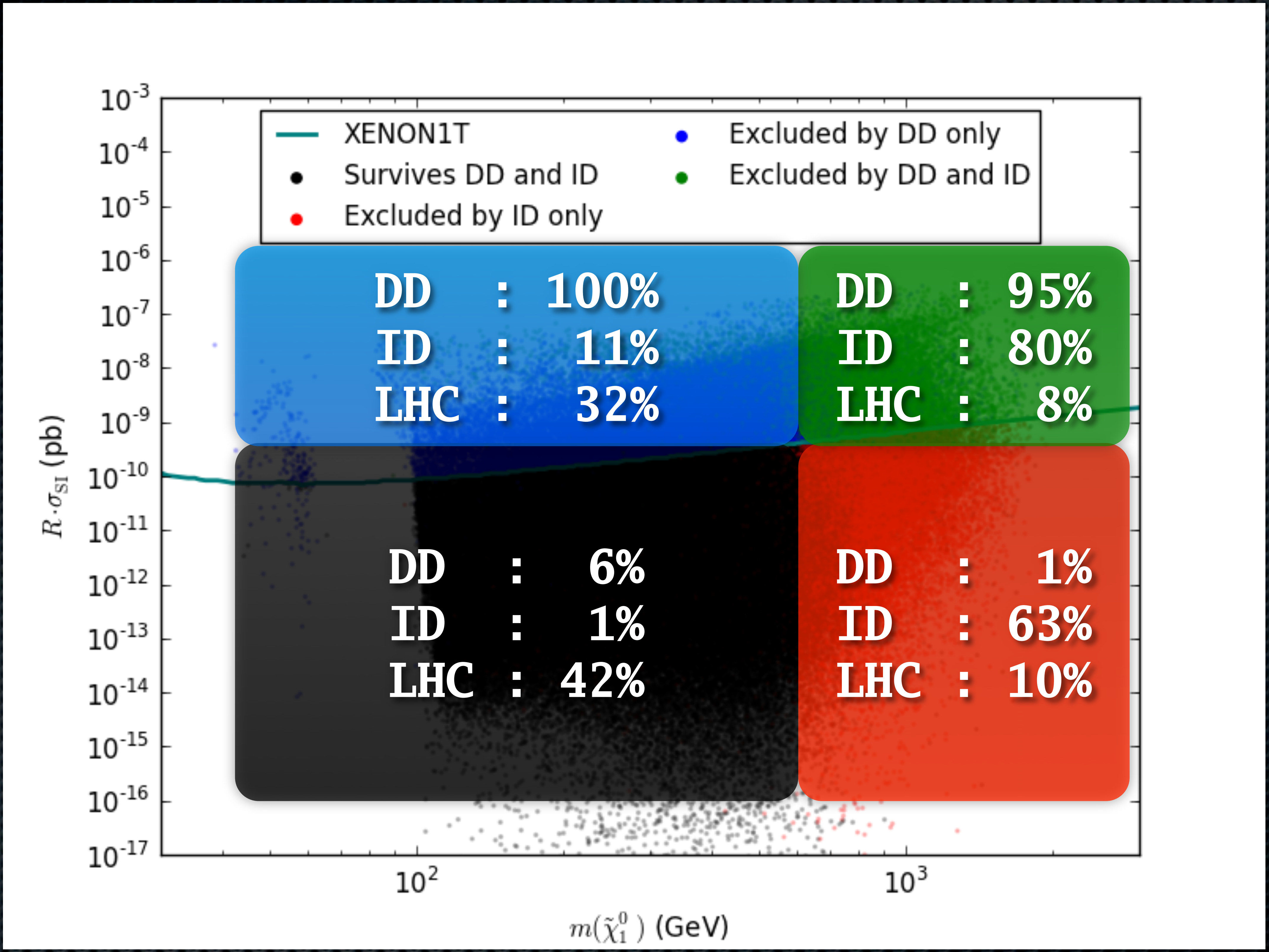


XENON1T
Survives LHC and ID
Excluded by ID only
Excluded by LHC only
Excluded by LHC and ID
$R \cdot \sigma_{SI}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)



Colliders
m_LCP (GeV)
10^3
m_χ̃0 (GeV)
10^2
10^3
pMSSM models after applying all searches except LHC
1
10
100
Spin-Independent Direct Detection
R ×σ_SI (pb)
m_χ̃0 (GeV)
pMSSM models after applying all searches except Xenon
Spin-Dependent Direct Detection
R ×σ_SD (pb)
m_χ̃0 (GeV)
pMSSM models after applying all searches except IceCube
Indirect Detection
Higgsinos
Winos
σv ×R^2 (cm^3 s^-1)
m_χ̃0 (GeV)
pMSSM models after applying all searches except Fermi+CTA
1000


XENON1T
Survives DD and ID
Excluded by ID only
Excluded by DD only
Excluded by DD and ID
$R \cdot \sigma_{SI}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$
$10^{2}$
$10^{3}$


XENON1T
Survives DD and ID
Excluded by ID only
Excluded by DD only
Excluded by DD and ID
DD : 100%
ID : 11%
LHC : 32%
DD : 95%
ID : 80%
LHC : 8%
DD : 6%
ID : 1%
LHC : 42%
DD : 1%
ID : 63%
LHC : 10%
$R\cdot\sigma_{SI}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$
$10^2$
$10^3$

# Conclusions

- Indirect detection is approaching the tip of the SUSY iceberg.
- A high-mass Wino/Higgsino band lies just below the surface.
- Indirect detection constraints will meaningfully impact high-mass models
    - Regions of high-mass, low scattering cross section may only be detectable through indirect means (complementarity in constraint).
    - Region of extensive overlap between direct and indirect detection provide multiple handles for characterization (complementarity in detection).

# Back Up

# Joint Likelihood Analysis

- Assume same dark matter particle in all dwarf spheroidal galaxies
- Perform a combined likelihood analysis of multiple dwarfs
  - Predicted flux for each dwarf will depend on individual dark matter content (J-factor)
  - Include statistical uncertainties from stellar kinematic data.
  - Fit backgrounds independently for each dwarf
- Joint likelihood function:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

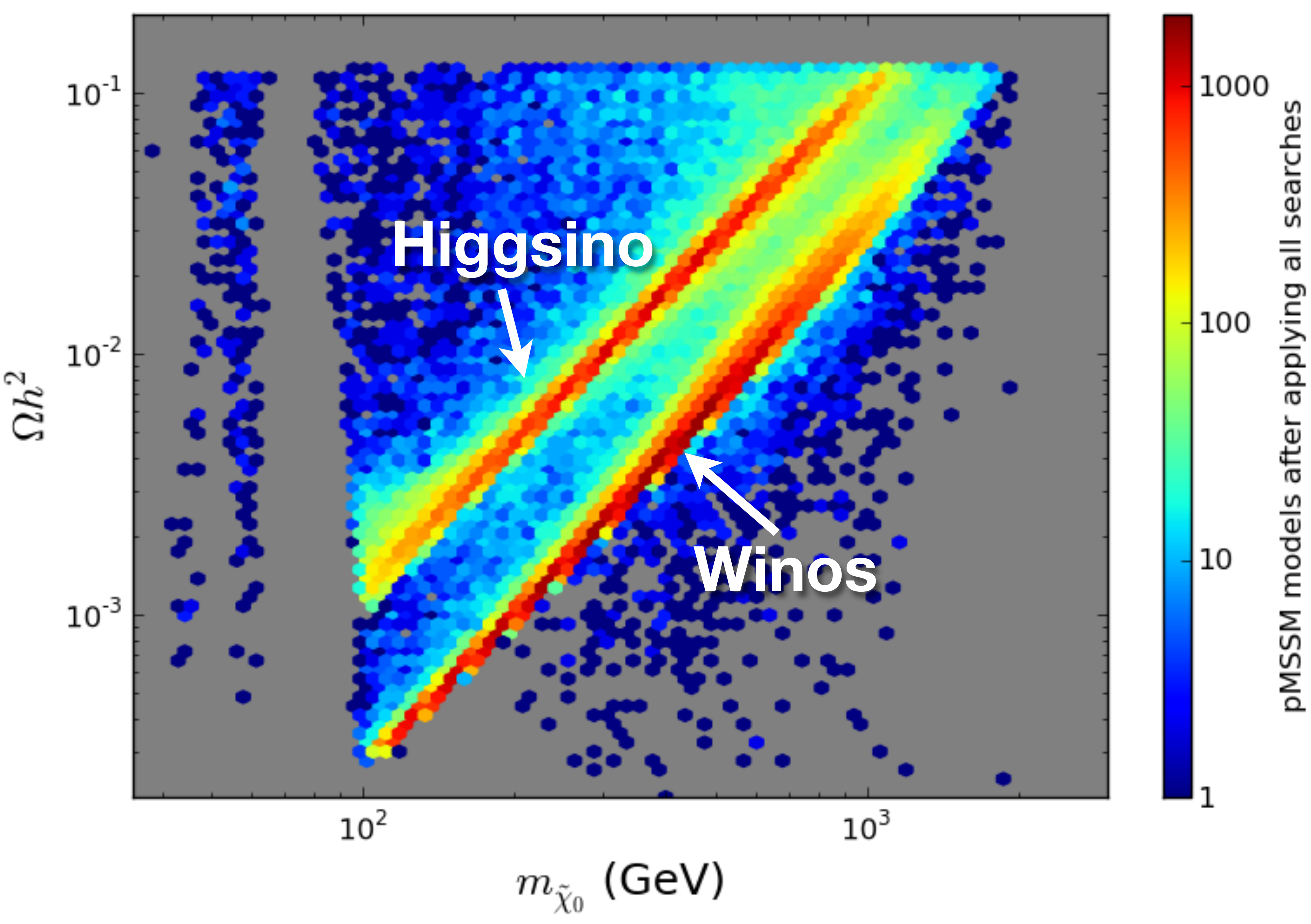
$$L(D\,|\,\mathbf{p_m}, \{\mathbf{p_k}\}) = \prod_k L_k^{\mathrm{LAT}}(D_k\,|\,\mathbf{p_m}, \mathbf{p_k}) \times \frac{1}{\ln(10) J_k \sqrt{2\pi}\sigma_k} e^{-(\log_{10}(J_k) - \overline{\log_{10}(J_k)})^2/2\sigma_k^2}$$

Shared by all dwarfs (dark matter particle parameters)

Fit for each dwarf (background sources)

Uncertainty in J-factor

Ackermann et al., arXiv:1108.3546



Higgsino
Winos
$10^{-1}$
$10^{-2}$
$10^{-3}$
$\Omega h^2$
$10^2$
$10^3$
$m_{\tilde{\chi}_0}$ (GeV)
1000
100
10
1
pMSSM models after applying all searches